14:47:07 OCA PAD AMENDMENT - PROJECT HEADER INFORMATION 07/03/90

Active

Project #: E-25-672 Cost share #: Rev #: 4
Center # : R6689-0A0 Center shr #: OCA file #:
Work type : RES
Contract#: 90085045 Mod #: 2 Document : PO
Prime #: Contract entity: GTRC

Subprojects ? : N
Main project #:

Project unit: ME Unit code: 02.010.126
Project director(s):
BOOK W J ME (404)894-3247

Sponsor/division names: CINCINNATI MILACRON INC / GREENWOOD, SC
Sponsor/division codes: 202 / 089

Award period: 890215 to 900630 (performance) 900630 (reports)

Sponsor amount	New this change	Total to date
Contract value	0.00	113,261.00
Funded	0.00	113,261.00
Cost sharing amount		0.00

Does subcontracting plan apply ?: N

Title: STUDIES OF DYNAMICS OF EXISTING INDUSTRIAL ROBOTS

PROJECT ADMINISTRATION DATA

OCA contact: Ina R. Lashley 894-4820

Sponsor technical contact

JOSEPH SCHNELLE
()-

INDUSTRIAL ROBOT DIVISION
P O BOX 1327
GREENWOOD SC 29648

Sponsor issuing office

MICHAEL A CALARDO
()-

CINCINNATI MILICRON
P O BOX 1327
GREENWOOD SC 29648

Security class (U,C,S,TS) : U
ONR resident rep. is ACO (Y/N): N
Defense priority rating : N/A
N/A supplemental sheet
Equipment title vests with: Sponsor X GIT
PER ATTACHED PROPOSAL DATED 2/9/89.
Administrative comments -
NO-COST EXTENSION TO 6/30/90 IS AUTHORIZED.

GEORGIA INSTITUTE OF TECHNOLOGY
OFFICE OF CONTRACT ADMINISTRATION

NOTICE OF PROJECT CLOSEOUT

Closeout Notice Date 11/30/90

Project No. E-25-672 Center No. R6689-0A0

Project Director BOOK W J School/Lab MECH ENGR

Sponsor CINCINNATI MILACRON INC/GREENWOOD, SC

Contract/Grant No. 90085045 Contract Entity GTRC

Prime Contract No. ______

Title STUDIES OF DYNAMICS OF EXISTING INDUSTRIAL ROBOTS

Effective Completion Date 900630 (Performance) 900630 (Reports)

Closeout Actions Required:	Y/N	Date Submitted
Final Invoice or Copy of Final Invoice	Y	901126
Final Report of Inventions and/or Subcontracts	N	
Government Property Inventory & Related Certificate	Y	
Classified Material Certificate	N	
Release and Assignment	Y	901126
Other ______	N	

Comments ______

Subproject Under Main Project No. ______

Continues Project No. ______

Distribution Required:

Project Director	Y
Administrative Network Representative	Y
GTRI Accounting/Grants and Contracts	Y
Procurement/Supply Services	Y
Research Property Managment	Y
Research Security Services	N
Reports Coordinator (OCA)	Y
GTRC	Y
Project File	Y
Other ______	N
______	N

The George W. Woodruff
School of Mechanical Engineering

DYNAMICS OF EXISTING INDUSTRIAL ROBOTS

Submitted to

Cincinnati Milacron, Inc.
Industrial Robot Division

Georgia Institute of Technology
Atlanta, Georgia 30332

FINAL REPORT

DYNAMICS OF EXISTING INDUSTRIAL ROBOTS

Submitted to

Cincinnati Milacron, Inc.
Industrial Robot Division

James D. Huggins
Dr. Wayne J. Book
The George W. Woodruff School of Mechanical Engineering
Atlanta, Georgia 30332-0405

Georgia Tech Project No. E-25-672
Cincinnati Milacron Purchase Order 90085045

April 13, 1990

TABLE OF CONTENTS

ABSTRACT

Our primary goal was to determine characteristics of the control system used by the GM Fanuc S-420F robot using the existing programming language. The control system parameters were modified to enable faster robot motions. The first section discusses the control system investigations. The second section presents the results of the structural vibration modes as measured by the technical staff of Cincinnati Milacron and the change in structural frequencies after stiffening the base mounting of the GMF S-420F robot. This report is submitted to extend and amplify the verbal reports made on several occasions in the past 6 months.

SECTION I: CONTROL SYSTEM MEASUREMENTS

Methodology

1. Write programs for rapid robot movements using KAREL without any modifications to excite structural vibrations.

2. Modify the KAREL system parameters to allow for faster motion of the robot.

3. Input a noise signal to the control system while measuring the response of the endpoint of the robot and the motor torques induced in the S-420F to obtain a transfer function of the GMF controller.

Discussion

In order to understand the GMF control system, it was first necessary to understand the existing software and the programming language used by the GMF S-420F. The programming language, KAREL, has a Pascal-like structure in that variables and variable types must be declared in a separate section at the beginning of the program. Each program must have a BEGIN -- END loop. Other loops can be nested in the main program's loop. Subroutines can be used. There is also an INCLUDE command that allows use of other files in a program. More on the KAREL language can be found in The Karel Reference Manual.

Our first attempt to measure the S-420F's response used the existing KAREL language without any attempt to modify the control system parameters. A program was written to cause the robot to move a single joint in a small amplitude sinusoidal motion as rapidly as possible. Figure 1 shows the configuration of the robot for these tests. This is the same position used by Cincinnati Milacron Technical Staff for testing the structural vibrations. A second program was written for moves between two points in a stepwise manner to be executed as quickly as possible. Initially, neither of these programs excited the robot structure. The reason for this was that the software placed a limit on the minimum acceleration time so that the robot moved smoothly between the two points. The variables used to do this are $ACCEL_TIME1 and $ACCEL_TIME2. These can be changed by going directly to the KAREL menu or by going to the Non-Positional Data menu, setting the

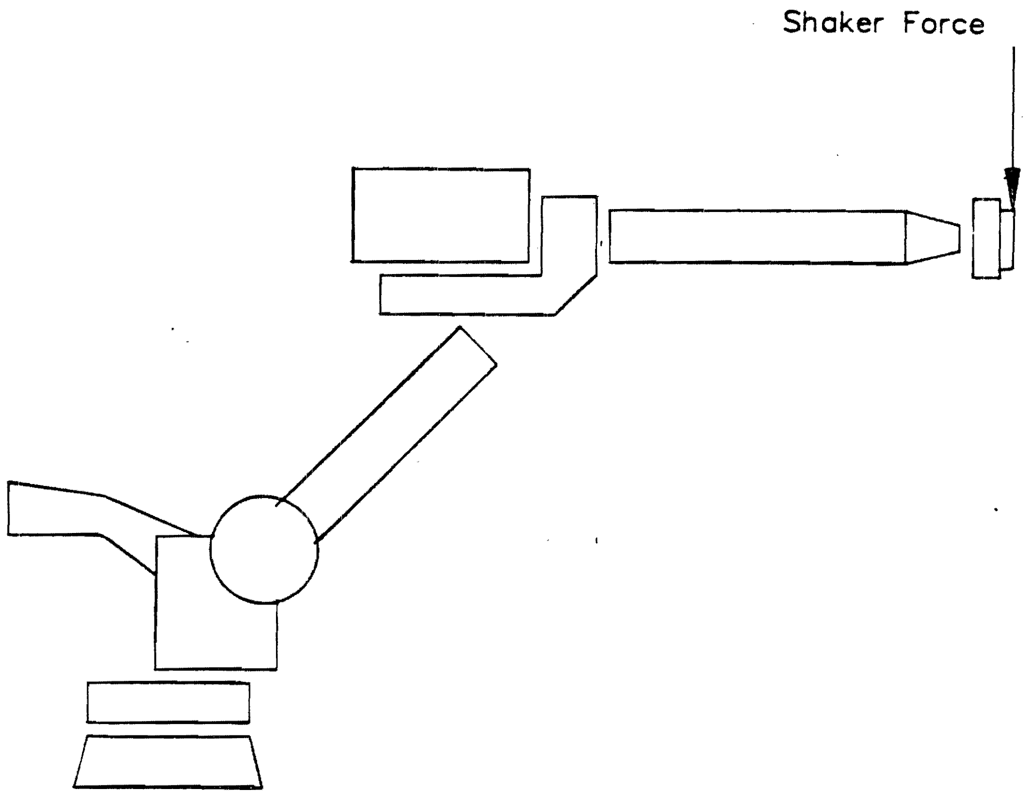


Figure 1. 45 Degree Configuration

system variable $ALL_SYSVARS to TRUE, then editing the SYSVARS.SYS file. See the KAREL Reference Manual, pg. 11-7. The $ACCEL_TIME1 and the $ACCEL_TIME2 variables originally were set to 320 and 160 milliseconds, respectively. Thus, the time is set to be a minimum of 480 milliseconds for moves between points that are close together. This strategy to avoid exciting the structural vibrations of the robot worked very well. Structural vibrations were very small and were damped out quickly.

Since our goal was to excite the structural vibrations, the system parameters were changed. Table 1 shows the new values used for the system variables. The gains were set to their maximum values. The acceleration times were set to their minimum values. (Note that the control system must be rebooted in order for the new system variables to take effect.)

Table 1

SYSTEM VARIABLE	OLD VALUE	NEW VALUE
$ACCEL_TIME1	320	1
$ACCEL_TIME2	160	1
$CART_ACCEL1	224	10
$CART_ACCEL2	128	10
$GAINS	20	50
$JNTVELLIM	1.57	3.14
$MIN_ACCTIME	480	2
$USEMAXACCEL	False	True
$ALL_SYSVARS	False	True

The program to repeat step motions was then run again. This time there was a large amplitude vibration of the robot. This was checked visibly since the vibrations were quite large. This suggests that the trajectory prescribed for the motion is responsible for minimizing the excitation of vibration. No evidence of sensing the vibrational behavior for feedback control was found.

It was noticed during this test that there was significant movement of the base of the robot due to bending of the 1 inch thick steel mounting plates that were used as mounting adaptors. The base was then stiffened by welding the mounting plate to the baseplate. Subsequent structural tests showed that stiffening the base shifted the 1st natural frequency upward by approximately 2.4 Hz. See Section II for more details.

To find a transfer function of the control system for the S-420F robot, random noise was used to provide an excitation to the control system. The robot was placed in the same configuration as it was for the structural tests (2nd link at 45 degrees from

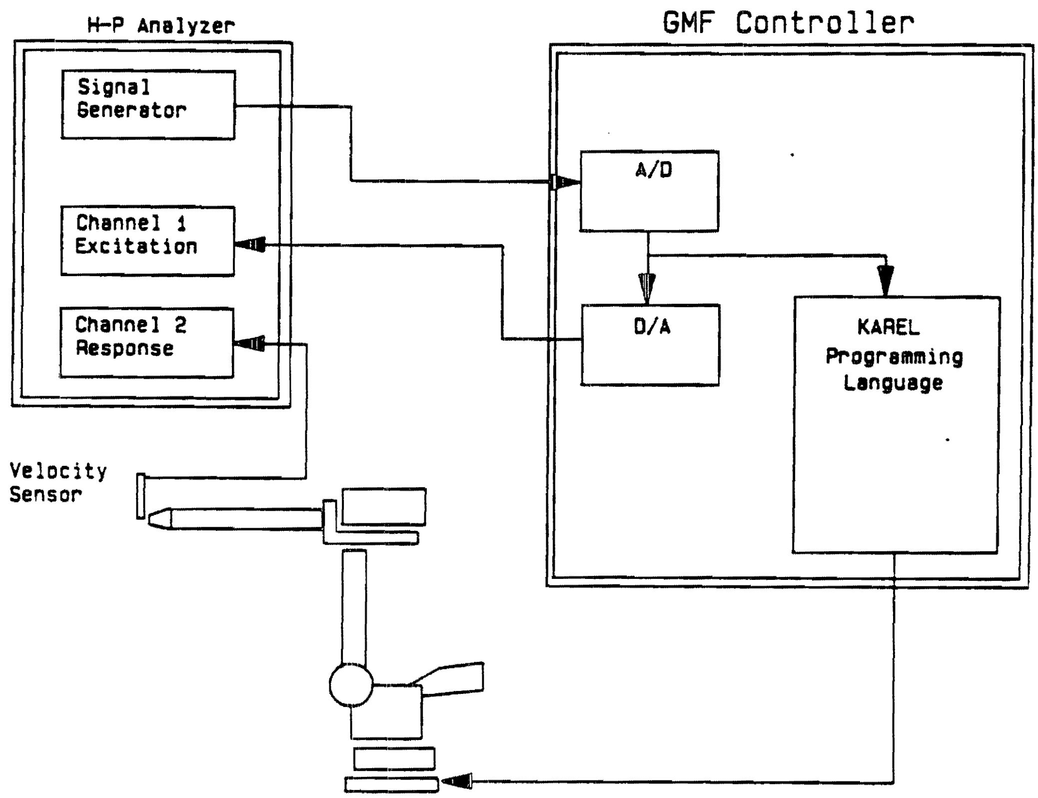


Figure 2. Signal Connections

vertical, 3rd link horizontal, See Figure 1). The random noise signal was input using the A/D converters that came with the Fanuc controller. Figure 2 is an schematic representation of the connections used. A Condition Handler routine was used along with the $deltaframe function to allow the noise signal to directly influence the robot's motion. Measurements of the frequency response (FRF) of the endpoint of the robot were made using an Hewlett-Packard 3562 signal analyzer. An IBM personal computer was also used to record the measurements were made since more than two channels of data could be gathered simultaneously using the PC's A/D board. The data measured with the PC were the velocity of the endpoint, the current signal to the motors, the input noise, and the input noise after being converted to a digital signal. The sample captured by the A/D converter was used to shift the commanded point and was sent out to the Hewlett-Packard signal analyzer via the D/A converter. This insured that the true excitation experienced by the controller was used by the analyzer. Figure 3 is an example of the plots of endpoint velocity in the vertical direction obtained using this method. Several features of the controller were discovered during these tests. First, a new signal is sent to the servos every 32 milliseconds. Second, the

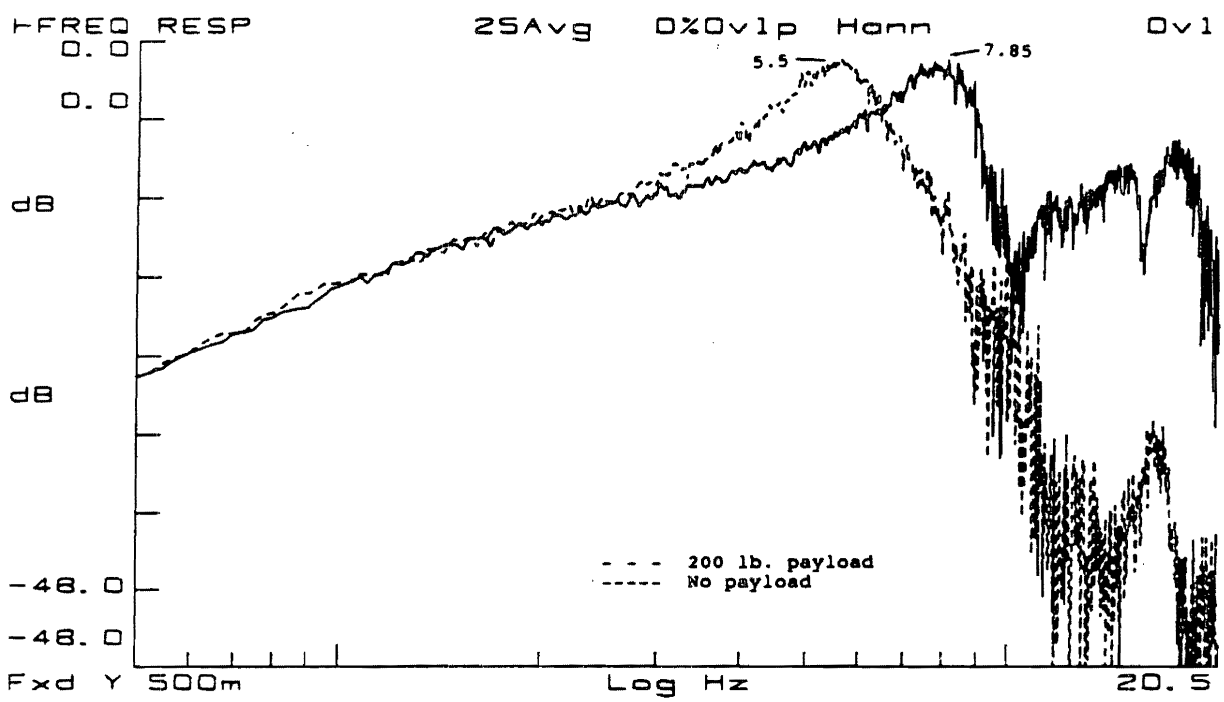


Figure 3. FRF, vertical direction, 45 deg. configuration
Input - digitized random noise
Output - Endpoint velocity

condition handler is said to be monitored every 32 to 64 milliseconds. The effect of this could be seen when measuring the motor current signal. Thirty two millisecond wide blocks were easily seen. This 32 millisecond sampling period means that the robot cannot respond to any signal faster than 15.6 Hz. That is,

$$\frac{1}{.032\ sec} = 31.25\ Hz.$$

Then, by the Nyquist criterion

$$\frac{31.25}{2} = 15.625\ Hz.$$

As can be seen in Figure 3, there is a roll off in response above 10 Hz. This is attributed to the 32 millisecond sampling time.

Two types of motion were used to measure the frequency response of the S-420F. The first was motion in the vertical direction. (See Figure 3.) The second was motion in the horizontal direction. The vertical motion was used to measure the response of the 3rd joint. The horizontal motion was used to measure the response of the 2nd joint. Figure 4 is the frequency response in the horizontal direction. As can be seen, there is very little difference in response when the 200 lb. payload is added. The payload is a smaller fraction of joint 2's total load than it is for joint 3. The motor and control gains are sized for larger

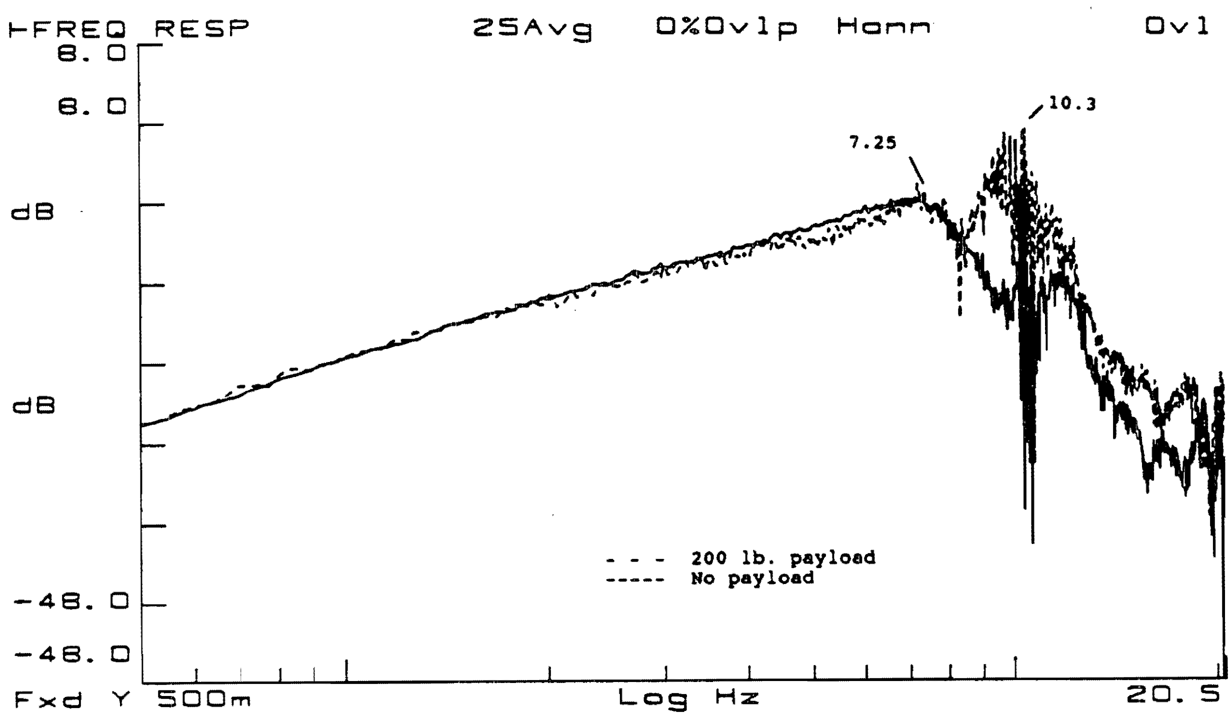


Figure 4. FRF, Horizontal Direction, 45 deg. Configuration
Input - Digitized Random Noise
Output - Velocity of Endpoint

inertias. The bandwidth appears to be limited by the control algorithm in a manner unaffected by payload size.

Figure 3 is the response in the vertical direction of the endpoint of the robot to the random noise input. There is a considerable difference in the vertical response when the 200 lb. payload is added. Figure 5 is the response of the endpoint velocity of the robot to an electromechanical shaker. Comparing Figures 3 and 5 shows the effect of the robot's controller. In Figure 5, the frequency response with no payload shows a 9.4 Hz peak. In Figure 3, the same peak is shifted back to 7.85 Hz and its peak is considerably less sharp. The rounded peak indicates damping added by the control system and other components between the controller and the endpoint. A similar result can be seen for

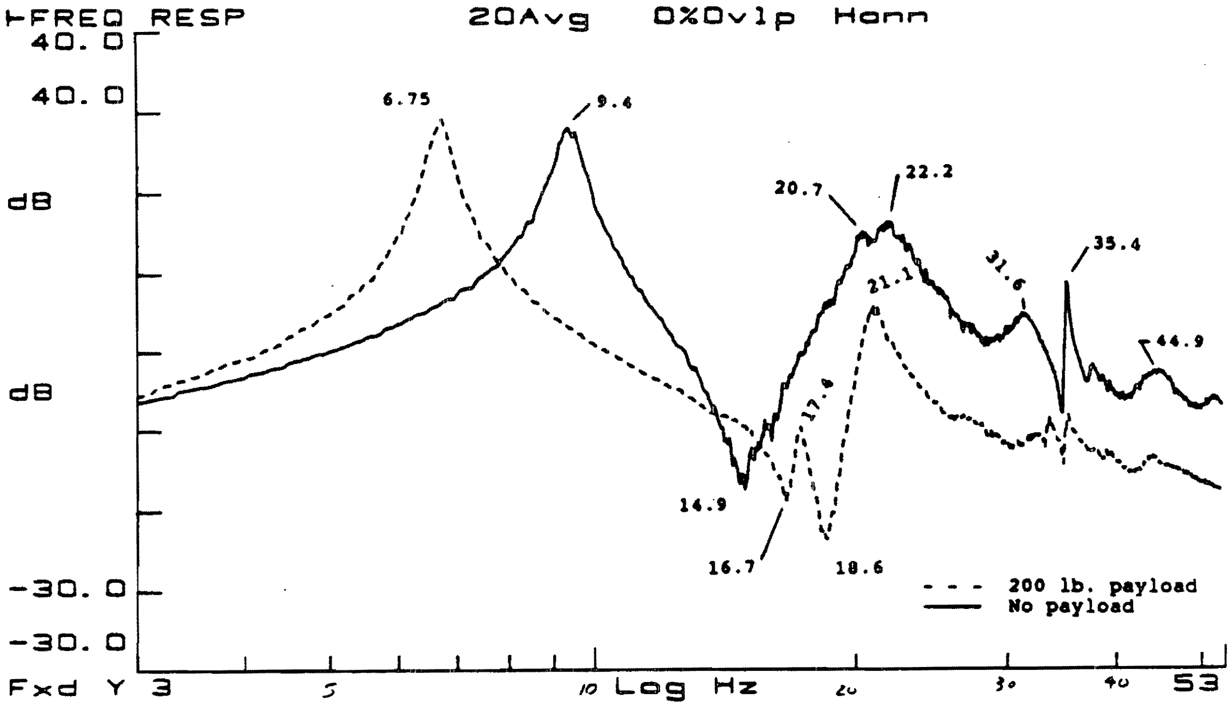


Figure 5. FRF using shaker, 45 deg. configuration
Input - Random Noise
Output - Endpoint velocity, Vertical

the 200 lb. payload case. The response of the robot's structure when tested with the shaker was 6.75 Hz. When tested using the control system, the response was 5.5 Hz. The lower frequency is attributed to additional compliance in the drive and controller which participates in the motion and "softens" the system when the motors are active. The phase angle of these responses (not shown here) show a large time delay, approximately 320 milliseconds, between the echo of the analog input and the system's response. The delay is apparently outside the feedback loop because such large delays would be very destabilizing. This delay has no effects on our conclusions based on the magnitude plots so long as it remains constant.

The measurements taken with the IBM personal computer involving the motor torques have not yet been analyzed. It is complicated by the pulse width modulated power supply of three phase power.

SECTION II.

Structural Measurements

Cincinnati Milacron corporate R & D Technical services personnel performed a structural analysis using their own equipment. A single configuration as seen in Figure 1 was used. Two separate tests were done. In the first set of tests, the robot was excited using a shaker attached at the endpoint of the robot in the vertical direction. The second set of measurements was made with the shaker attached to the endpoint of the robot but mounted at 90 deg. to the first location of the shaker. See Figure 6. Measurements of the vibration of the robot were made using triaxial accelerometers (strain gage type) mounted at numerous locations on the robot. The first set of tests were intended to measure vibrations excited in the plane of the robot's links. The second measured vibrations out of the plane of the robot's links.

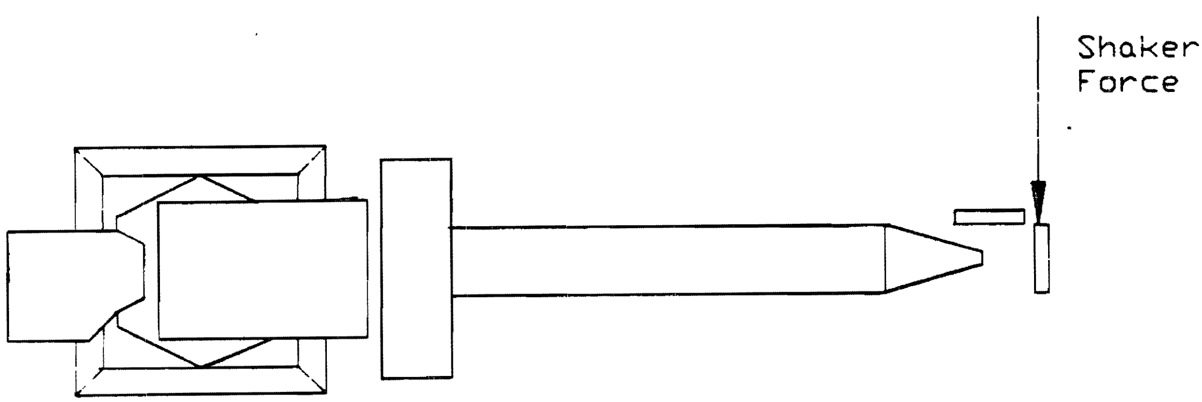


Figure 6. Top View showing shaker position

Additionally, the shift of the structural frequencies with payload was measured by adding a 200 lb. payload to the end of the robot. The results of the structural testing by Cincinnati Milacron are as follows:

IN-PLANE EXCITATION

No Payload	200 lb. Payload
7 Hz	5.25 Hz
13.8 Hz	9.50 Hz
17.6 Hz	18.00 Hz

OUT-OF-PLANE EXCITATION

No Payload	200 lb. Payload
5.8 Hz	4.6 Hz
14.0 Hz	13.0 Hz
20.3 Hz	22.0 Hz

Figures 7-9 show the mode shapes of the S-420F robot in response to the in-plane excitation. Figures 10-13 show the mode shapes in response to the out-of-plane excitation. Figure 14 shows the frequency response of the acceleration of the driving point of the robot in response to the in-plane excitation with no payload. Figure 14a. is the same response after adding a 200 lb. payload. Figure 15 shows the frequency response of the acceleration of the driving point of the robot in response to the out-of-plane excitation. Figure 15a. is the frequency response after the 200 lb. payload is added.

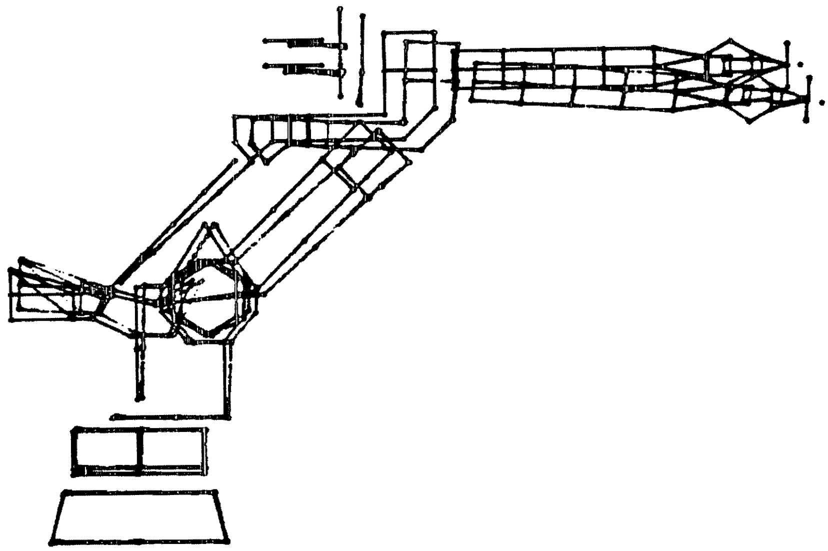


Figure 7. First Mode Shape, 7 Hz., In-plane Excitation

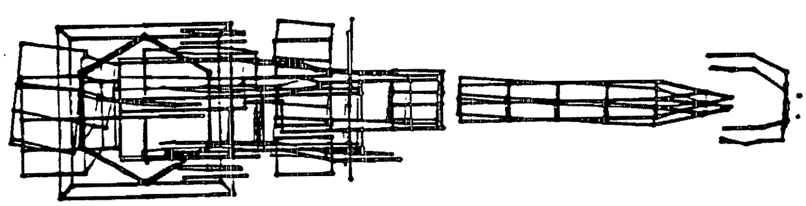


Figure 8. Second Mode Shape, 13.8 Hz., In-plane Excitation

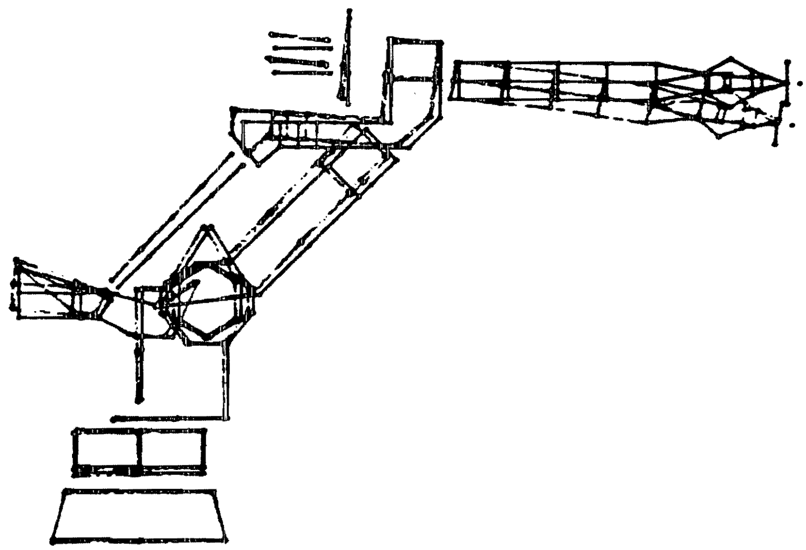


Figure 9. Third Mode Shape, 17.6 Hz., In-plane excitation

In plots made of the mode shapes, a noticeable motion of the base of the robot can be seen. However, no attempt was made during Cincinnati Milacron's testing to eliminate the base's motion because it was said that the vibration analysis software could compensate for the base motion.

During subsequent testing at Georgia Tech, it was decided to stiffen the base of the robot because the motion of the base was relatively large when the robot moved at high speeds. This was done by welding the spacers under the robot to the baseplate. Tests similar to the ones performed by Cincinnati Milacron were done in order to compare the change in frequencies. Additionally, a different configuration was tested in which the robot was the robot was excited by an electro-magnetic shaker in the in-plane direction only. Measurements were made of the driving point

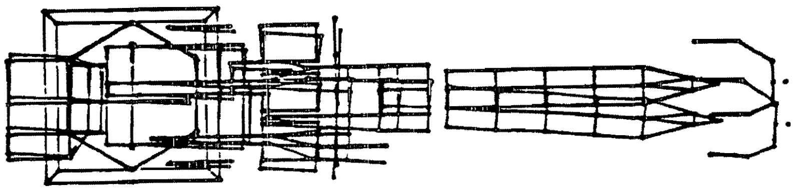


Figure 10. First Mode Shape, 5.8 Hz., Out-of Plane Excitation

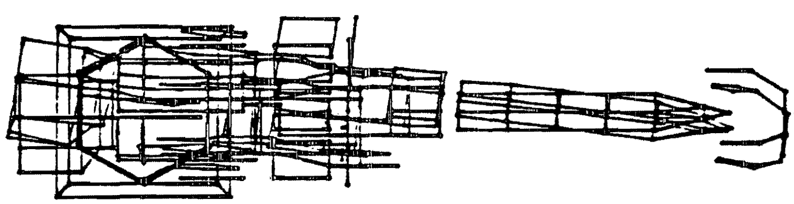


Figure 11. Second Mode Shape, 14 Hz., Out-of-Plane Excitation

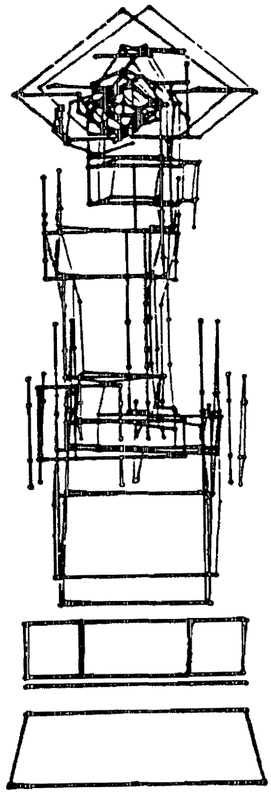


Figure 12. Second Mode Shape, 14 Hz., Front View

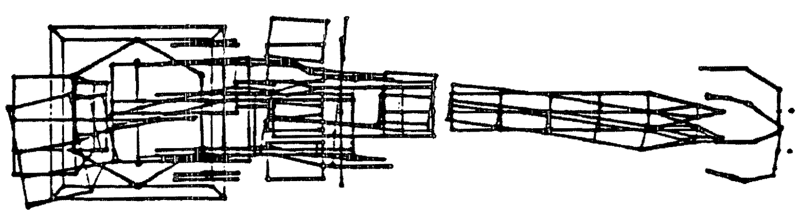


Figure 13. Third Mode Shape, 20.3 Hz., Out-of-plane excitation

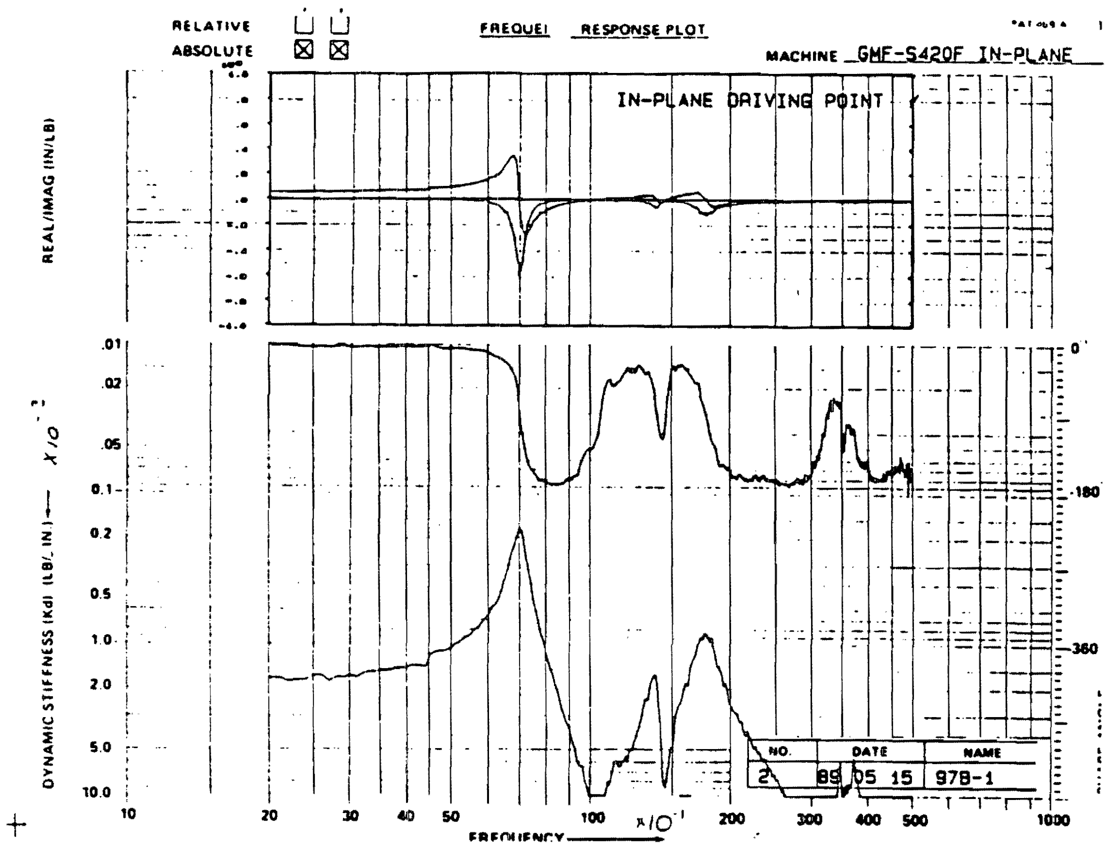


Figure 14. FRF of driving point, No payload, In-plane

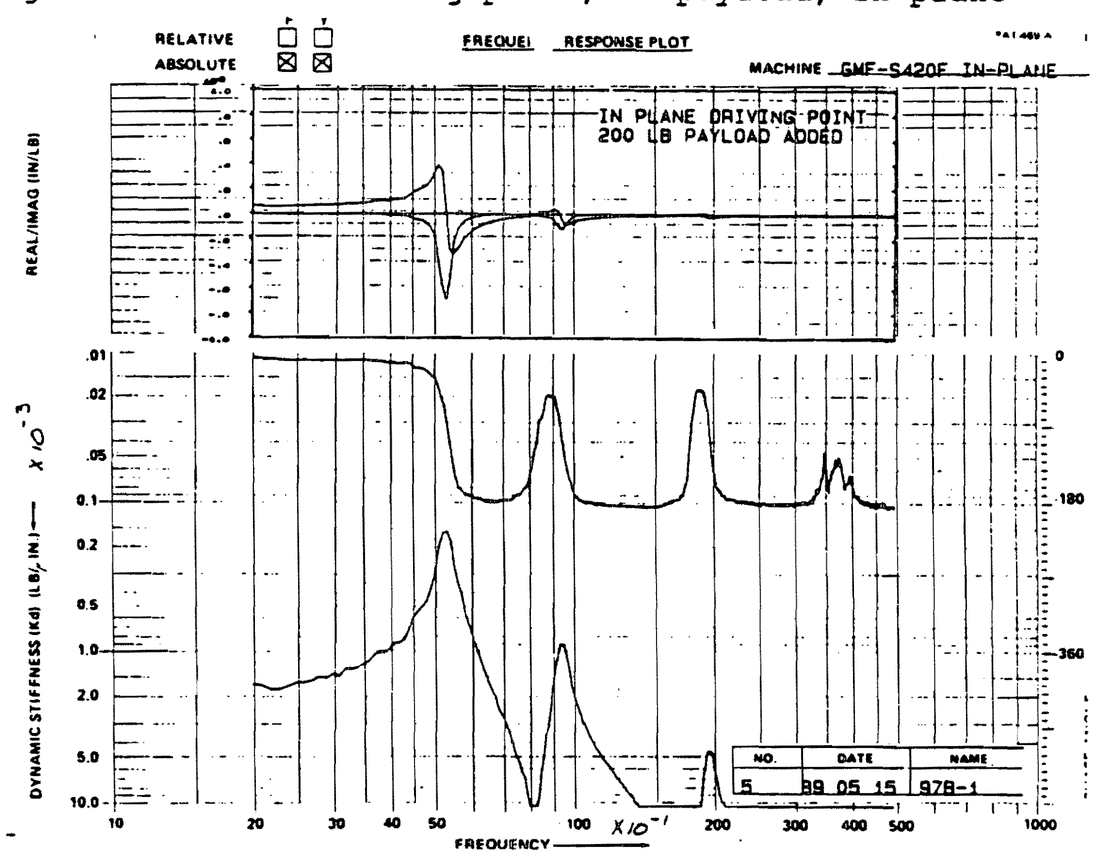


Figure 14a. FRF of driving point, 200 lb. payload, In-plane

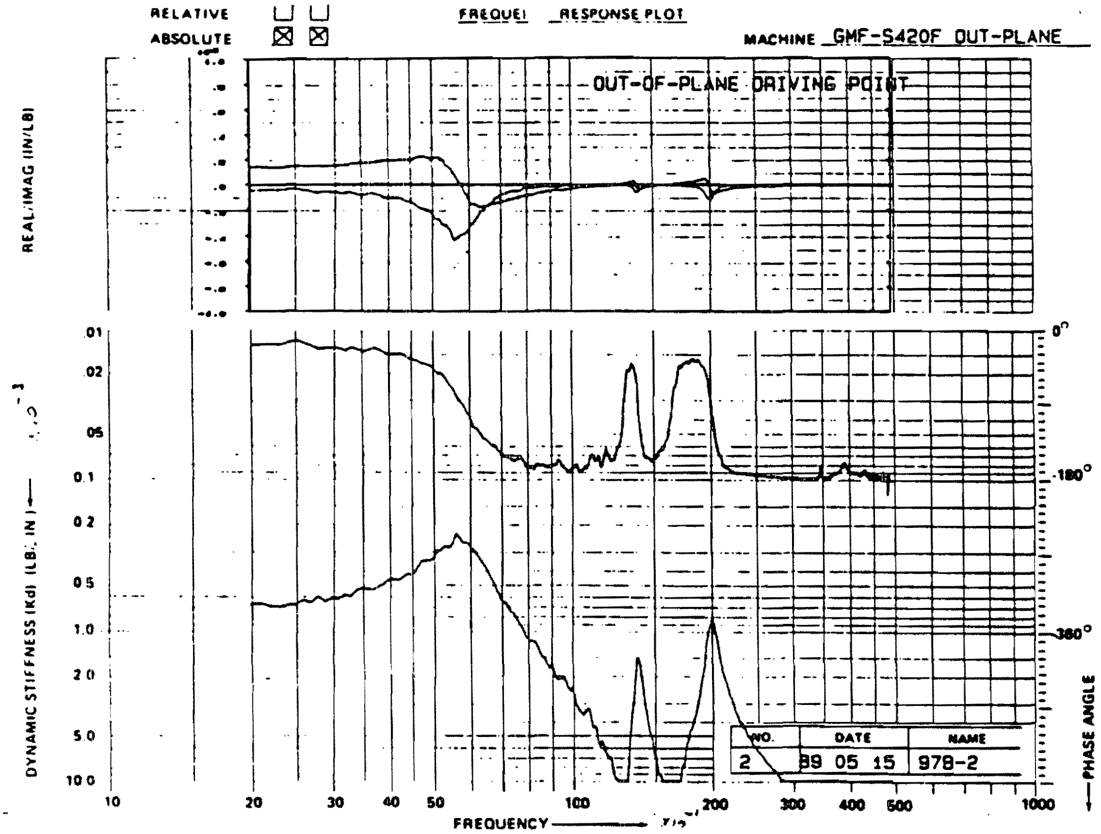


Figure 15. FRF of driving point, No payload, Out-of-plane

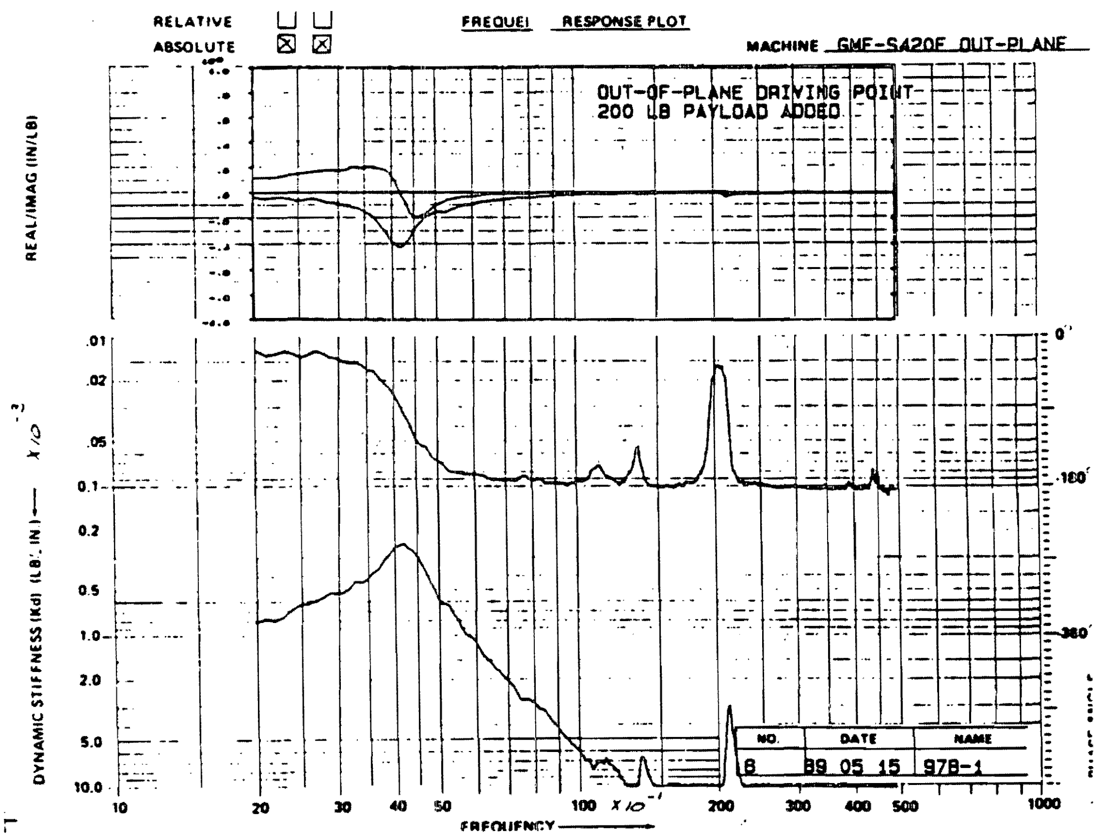


Figure 15a. FRF of driving point, 200 lb. payload, Out-of-plane

retracted so that the second and third links formed a 90 deg. angle with the second link being perpendicular to the floor and the third link was parallel to the floor. This is referred to as the 90 deg. configuration. See Figure 16. Note that in these tests,

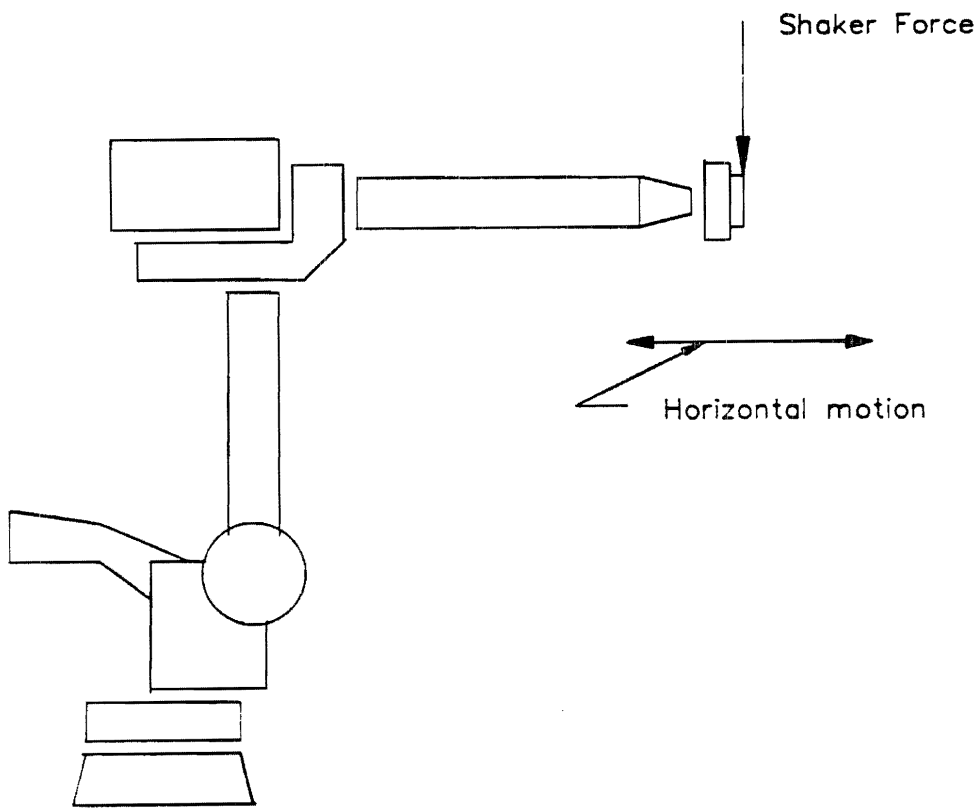


Figure 16. 90 Degree Configuration

the robot was excited by an electro-magnetic shaker in the in-plane direction only. Measurements were made of the driving point velocity only. The results found using the stiffened base are as follows:

45 DEG. CONFIGURATION

No Payload	200 lb. Payload
9.4 Hz	6.75 Hz
20.7 Hz	17.40 Hz
22.2 Hz	21.10 Hz

90 DEG. CONFIGURATION

No Payload	200 lb. Payload
9.2 Hz	7.4 Hz
13.1 Hz	12.7 Hz
18.9 Hz	17.6 Hz

Figures 17 and 18 show the frequency response of the velocity of the endpoint of the robot in the 90 degree configuration. Figure 17 is the response in the vertical direction using the servos to excite the structure. Figure 18 is the response in the vertical direction using the shaker to excite the structure. Note the shift in frequencies in Fig. 18 due to the addition of the 200 lb. payload.

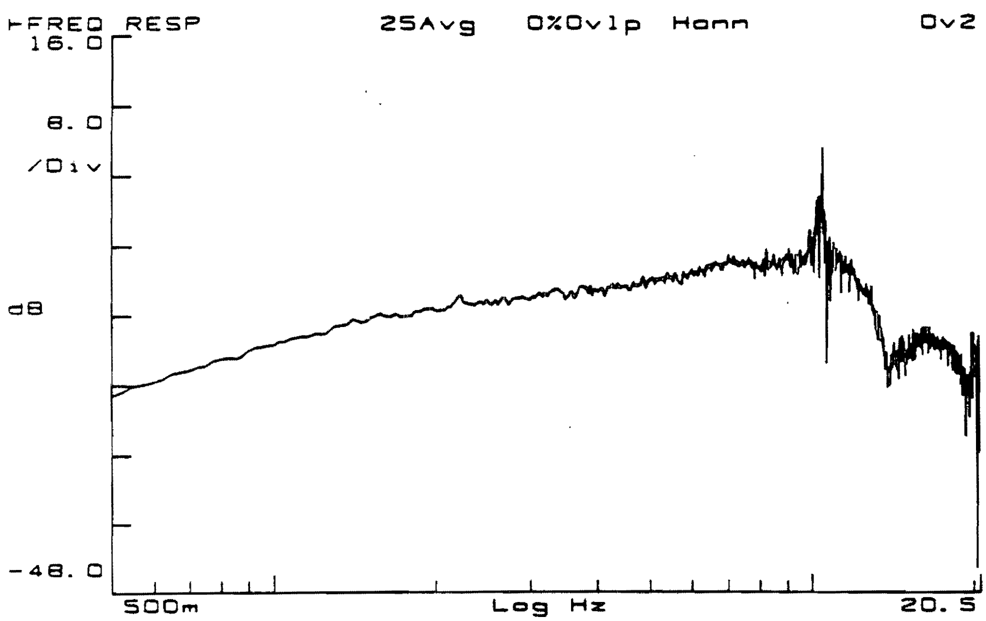


Figure 17. FRF 90 degree configuration, vertical response using servos to excite the robot.

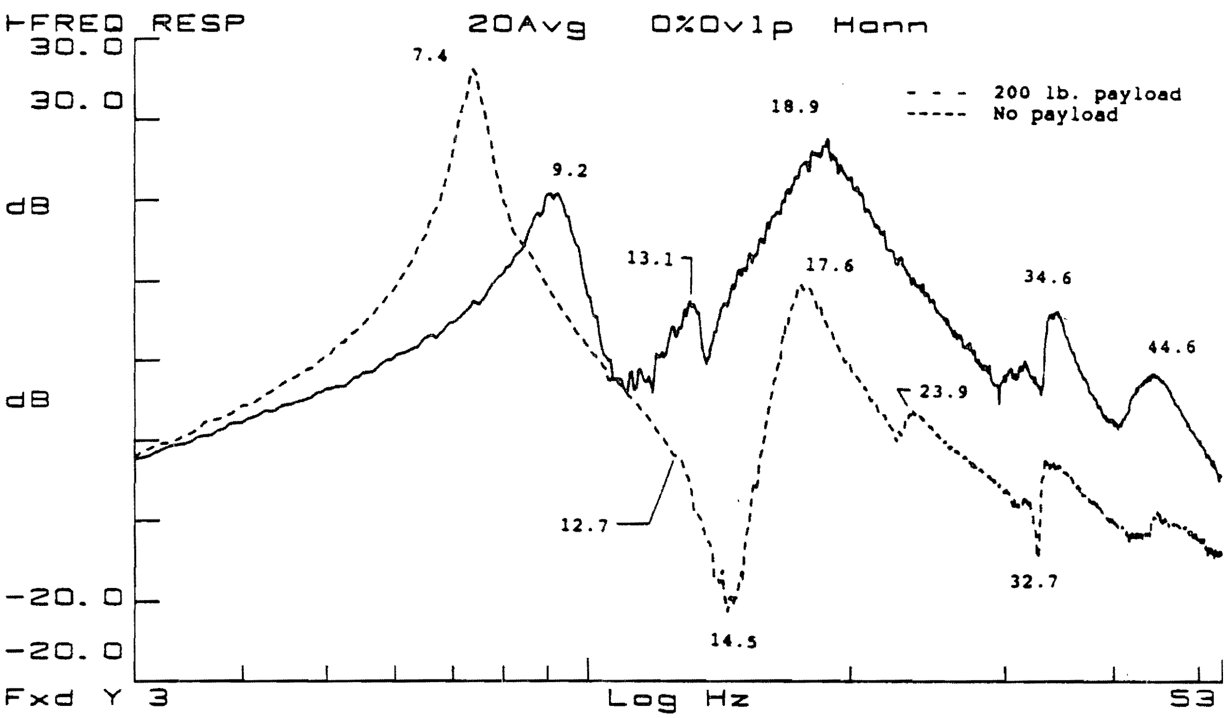


Figure 18. FRF, 90 deg. configuration, horizonal response using shaker to excite the robot structure.

SUMMARY

1. The vibration frequencies of the robot are damped by the control system.
2. No attempt with feedback control was observed to dynamically compensate for structural vibrations other than using a smooth acceleration profile with a minimum time.
3. The bandwidth of horizontal motions of the robot is unaffected by the size of the payload.
4. The stiffening of the base of the robot significantly increased the frequency of the 1^{st} mode.
5. A shift of the frequency response due to payload changes is seen in the vertical direction.

APPENDIX I

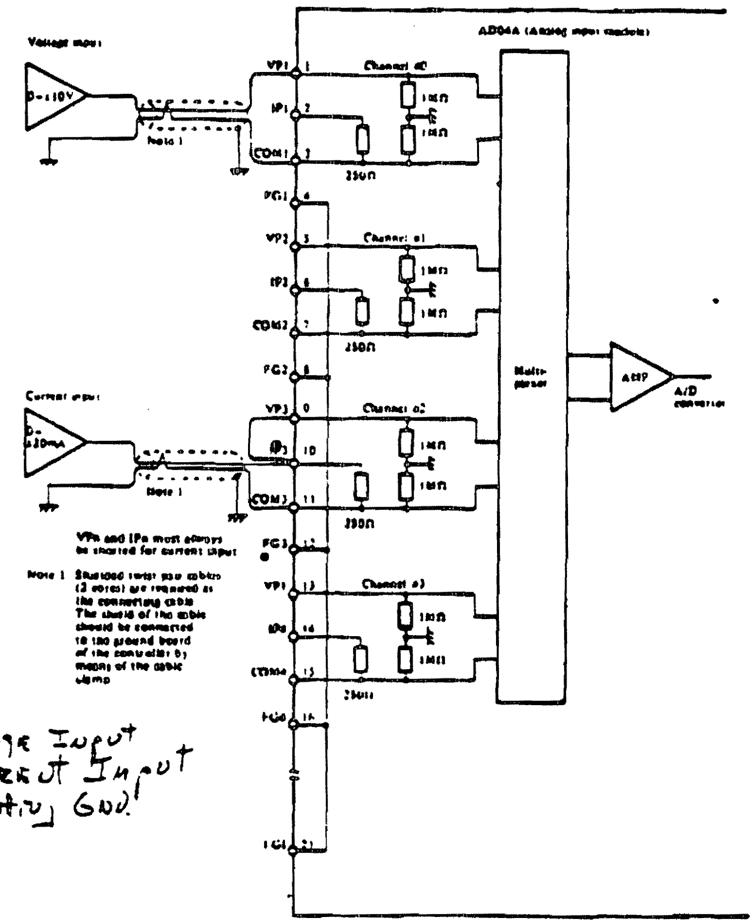
A/D and D/A Conversions for use with $DELTAFRAME

The following section contains some information not found in the manuals received from GMF Fanuc and describes some difficulties encountered during tests of the S-420F robot. Figures 19 and 20 are the connection diagrams for the analog to digital module, AD04A, and the digital to analog module, DA02A, respectively. The diagrams show that the modules can be used in voltage or current mode. The information on setting up the analog inputs and outputs from the software side was well documented (See pages 6-1 to 6-25 in the KAREL Reference Manual), but the wiring connections were not included in the manuals shipped with the robot.

To measure the control system characteristics, the noise signal was input to the A/D module. See Figure 2. The $deltaframe feature of KAREL allows the Fanuc robot to respond directly to an external input bypassing the usual path planning section of the controller. The $deltaframe feature must be used in conjunction with a condition handler routine. The condition handler routine monitors inputs to the KAREL system. The $deltaframe feature is not well documented and there are no examples given in the manuals. After a few calls to GMF Fanuc, an example was sent to Georgia Tech. See Figure 21. One difficulty with using the condition handler routines is that they are only monitored at a minimum of 32 milliseconds. Usually, the monitoring time is longer. This limits the bandwidth of response of the robot as discussed in Section I.

Table 3.4 (i) Analog input module

Module name	Input points	Analog inputs	Resolution	Accuracy	Max input voltage/ current	External connection
AD04A	4 points/ module	-10 - +10 VDC (Input resistor 1 MΩ) -20 - +20 mADC (Input resistor 250 Ω) can be selected.	5 mV 20 μA	±0.5% or less	±15 V ±40 mA	Terminal block (M3)



VP = Voltage Input
IP = Current Input
FG = Floating GND

Fig. 3.4 (i) Analog input module connection

3-65

Figure 19. GMF Fanuc AD04A wiring diagram

Table 3.4 (k) Analog input module

Module name	Output points	Analog outputs	Resolution overall accuracy	Isolated	External connection
DA02A	2 points/ module	-10 - +10 VDC (External load resistance more than 1 KΩ) 0 - +20 mA DC (External load resistance 0 - 500 Ω) can be selected.	5 mV, within 20 μA 0.5%	Not isolated	Terminal board (M3)

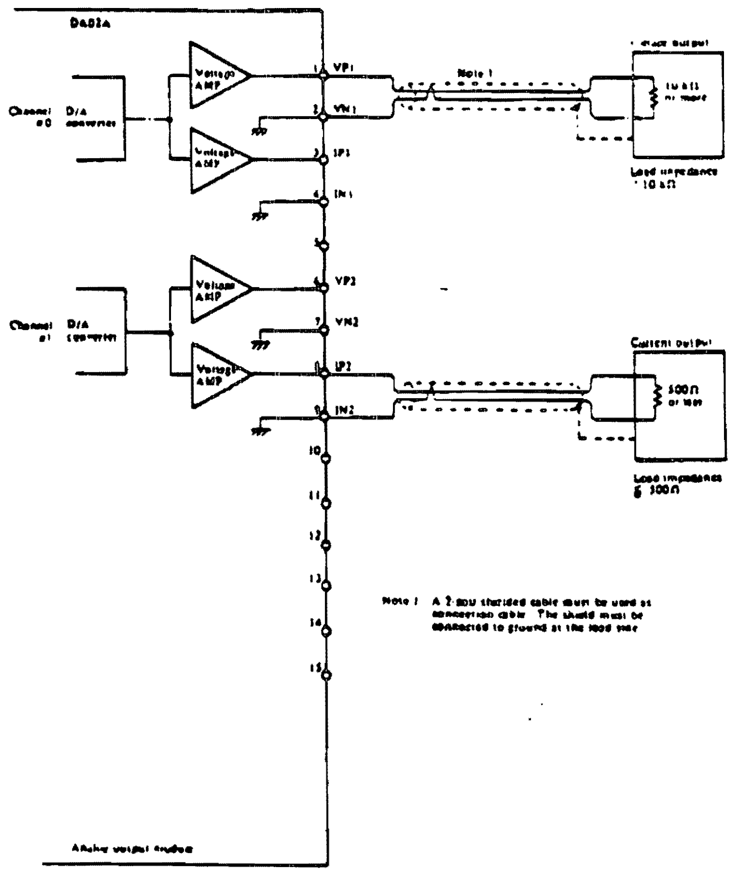


Fig 3.4 (j) Analog output module connection

3-66

Figure 20. GMF Fanuc DA02A wiring diagram

The last problem encountered was a hardware problem with the Fanuc drive controller on the 2nd joint. Since the voltage signal proportional to the drive current has a high voltage level, an isolation amplifier was needed to monitor the output current. The problem with the drive occurred when the lines used to monitor the current were disconnected. Upon removing the wires, there was an immediate fault with the second joint. After being informed of the problem, GMF Fanuc replaced the drive board under the warranty. The second board was received very quickly, in approximately two days. The problem reoccurred several days later but was an intermittent problem. The robot was shipped to SC before the second occurance of this was resolved.

Since the isolation amplifiers used have a very high impedence, it is unusual to think that simply disconnecting them from the circuit would cause a surge in current. This may be a problem in future testing of the robot.

APPENDIX II

Current Research: Advanced Control for the Cincinnati Milacron 646 robot

The current research objectives with the Cincinnati Milacron 646 robot are to implement a digital controller using multivariable control and trajectory planning. Since this places a large computational burden on the robot's controller, the new controls will be implemented using a digital signal processing (DSP) system. A disadvantage that most DSP processors have when using higher level programming languages is that the code produced by the high level languages is very inefficient. The DSP system chosen from dSpace in West Germany excels in producing efficient code for control algorithms. The DSP hardware from dSpace is capable of very high speed computation and has the added advantage of being compatible with the current operating system in the 646 so that any controllers developed could be quickly implemented in the existing system.

The dSpace hardware uses the Texas Instruments DSP chip, TMS320C25, a fixed point processor with a 100 nanosecond cycle time as part of a system that is installed in an AT-class personal computer utilizing the AT bus for communications with the host computer. Included with the system is 64k bytes of program memory, 59k of data memory, and a 4k byte section of true dual ported memory. The memory is mapped into the host's memory so that both the DSP system and the host computer can access the memory at any time. The dual port memory section has separate data and address lines for high speed operation. Other dSpace hardware products available are analog-digital (A/D) converters, digital-analog (D/A) converters, an encoder board, and a digital timer board. These are linked via a separate, high speed, 32 bit wide bus to avoid the speed limitations of the AT bus.

The software provided by the dSpace is unique in that it is designed for developing controls. Controller and system equations are entered in state space form, ie.,

$$\dot{x} = Ax + Bu$$

and

$$y = Cx + Du$$

Provision is made for systems to be easily simulated before implementing controls including methods for modeling quantization and saturation effects, and for following trajectories. The software also automatically scales the system equations to avoid overflowing the DSP chip.

The DSP software includes a two stage compiler. The first stage produces a special DSP language called DSPL. This code can be edited to add additional terms for more advanced control strategies such as nonlinear or adaptive controllers. The second stage of the compiler produces a very efficient assembly language code including comments that can also be examined and edited.

Current equipment at Georgia Institute of Technology includes an 80386 based computer with an AT style bus, and a DS 1001 DSP board with corresponding software from dSpace. To allow the DSP controller to move the robot, the "REMOTE ENABLE" switch and circuits on the 646 were used. This allows the user to easily switch from the still operational control system that came with the robot to the DSP control system. All safety related equipment, such as stop buttons and the brake system, remains fully operational regardless of which controller is being used. Since the operating control system is disabled when using the DSP controller, parallel signals from the resolvers are used to provide position information to the DSP controller and to the original operating system. The only other parts of the original system that are functional when using the digital controller are the pulse width modulated motor amplifiers. All other functions of the original control system are made disabled.